TITLE: Application of Torsional Vibration Measurement to Shaft Crack Monitoring in Power Plants

APPLICATION OF TORSIONAL VIBRATION MEASUREMENT TO SHAFT CRACK MONITORING IN POWER PLANTS

Ken Maynard, Applied Research Laboratory,
Martin Trethewey and Charles Groover, Dept. of Mechanical Engineering

The Pennsylvania State University
State College, PA 16801

Abstract: The primary goal of the this project was to demonstrate the feasibility of detecting changes in shaft natural frequencies (such as those associated with a shaft crack) on rotating machinery in electric power generation plants using non-contact, non-intrusive measurement methods. During the operation of power plant equipment, torsional natural frequencies are excited by turbulence, friction, and other random forces. This paper primarily addresses the results of field application of non-intrusive torsional vibration sensing to a hydro station and to large induced-draft (ID) fan motors. Testing reaffirmed the potential of this method for diagnostics and prognostics of shafting systems. The first few shaft natural frequencies were visible, and, for the hydro station, correlated well with finite element results (finite element results are not available for the ID fan motors). In addition, several issues related to the development of the non-intrusive transducer were revealed.

Key words: Shaft cracking; condition based maintenance; failure prediction; torsional vibration.

Background: The detection of shaft natural frequencies in the torsional domain requires that the signal resulting from excitation of the rotating elements by turbulence and other random processes is measurable. If measurable, these natural frequencies may be tracked to determine any shifting due to shaft and blade cracking or other phenomena effecting torsional natural frequencies. Difficulties associated with harvesting the potentially very small signals associated with shaft vibration in the torsional domain could render detection infeasible. Thus, transduction and data acquisition must be optimized for dynamic range and signal to noise ratio [1, 2, 3].

The advantage of using shaft torsional natural frequency tracking over shaft lateral natural frequency tracking for detecting cracks in direct-drive machine shafts is twofold:

- A shift in natural frequency for a lateral mode may be caused by anything which changes the boundary conditions between the rotating and stationary elements: seal rubs, changes in bearing film stiffness due to small temperature changes, thermal growth, misalignment, etc. So, if a shaft experiences a shift in lateral natural frequency, it would be difficult to pinpoint the cause as a cracked shaft. However,

none of these boundary conditions influence the torsional natural frequencies. So, one may say that a shift in natural frequency in a torsional mode of the shaft must involve changes in the rotating element itself, such a crack, or perhaps a coupling degradation.

- Similarly, finite element modeling of the rotor is simplified when analyzing for torsional natural frequencies: these boundary conditions, which are so difficult to characterize in rotor translational modes, are near non-existent in the torsional domain for many rotor systems. This means that characterization of the torsional rotordyanamics of a system is much more straightforward, and therefore likely to better facilitate diagnostics.

Detection of the small torsional vibration signals associated with shaft natural frequencies is complicated by transducer imperfections and by machine speed changes. The use of resampling methods has been shown to facilitate the detection of the shaft natural frequencies by: (1) correcting for torsional transduction difficulties [2] resulting from harmonic tape imperfections (printing error and overlap error); and (2) correcting errors as the machine undergoes gradual speed fluctuation [3, 4]. In addition, correction for more dramatic speed changes was addressed in [4]. These corrections made laboratory testing quite feasible.

Transducer setup and methodology: The transducer used to detect the torsional vibration of the shaft included a shaft encoded with black and white stripes, an infrared fiber optic probe, an analog incremental demodulator and an A/D converter. The implementation of the technique under laboratory conditions was previously presented in [2, 3]. Figure 1 shows a schematic of the transducer system.

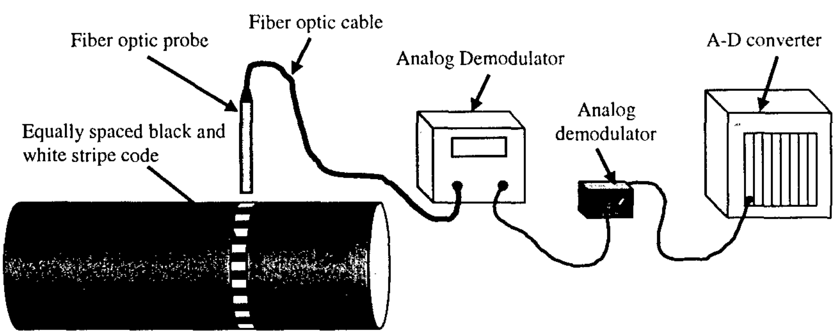

Figure 1: Schematic of transducer setup for torsional vibration measurement

Field implementation: The methodology was implemented on two power plant machines: one a hydroelectric plant turbine generator that has experienced cracking on its newly redesigned turbine rotor; the other a motor on an induced draft (ID) fan at a super-critical coal-fired plant that has experienced cracking of the web-shaft welds.

Hydro turbine: The hydro plant consists of five 3 MW electric turbine generators sets. The plant was originally built in about 1910, but it has recently been redesigned to eliminate an underwater, wooden (lignum vitae) bearing and improve efficiency. The layout of a unit is shown in Figure 2 and Figure 3.

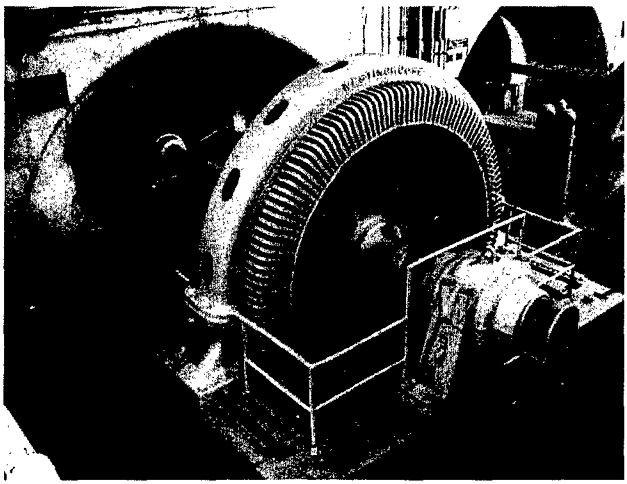

Figure 2: Hydro turbine-generator set

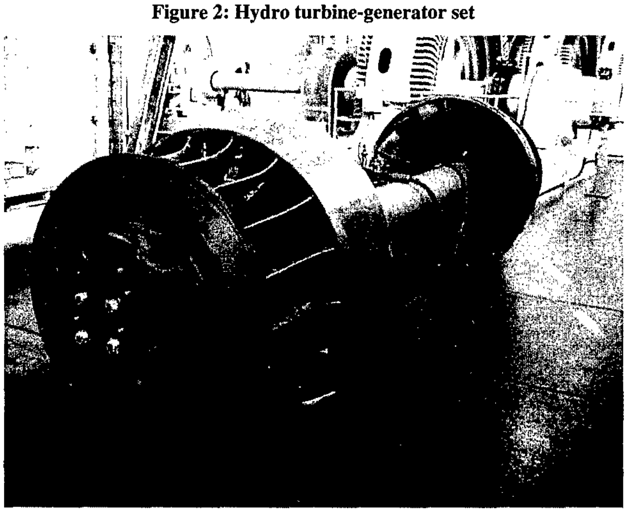

Figure 3: Disassembled Hydroturbine

However, in the last five years, three of the newly designed turbine rotors have experienced severe cracking. Instrumentation and analysis was performed on one of the units that had not experienced cracking to demonstrate the feasibility of detecting shaft

natural frequencies. Figure 4 shows the optic probe, tachometer, and encoded tape placement.

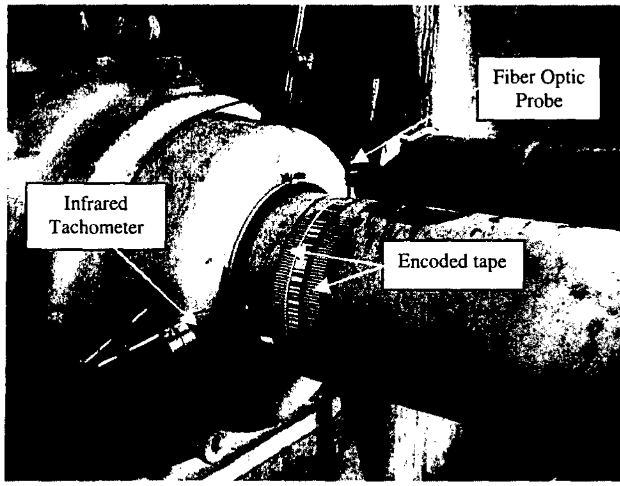

Figure 4: Optic probe, encoded tape, and tachometer placement

The data was analyzed using the double resampling technique [3,4] to eliminate the adverse effects of the presence of running speed and its harmonics on frequency identification. The results of four test runs are shown in Figure 5. Note the peaks at about 16 Hz and 41 Hz. These correspond well to the finite element model torsional frequencies of 16 Hz and 40 Hz.

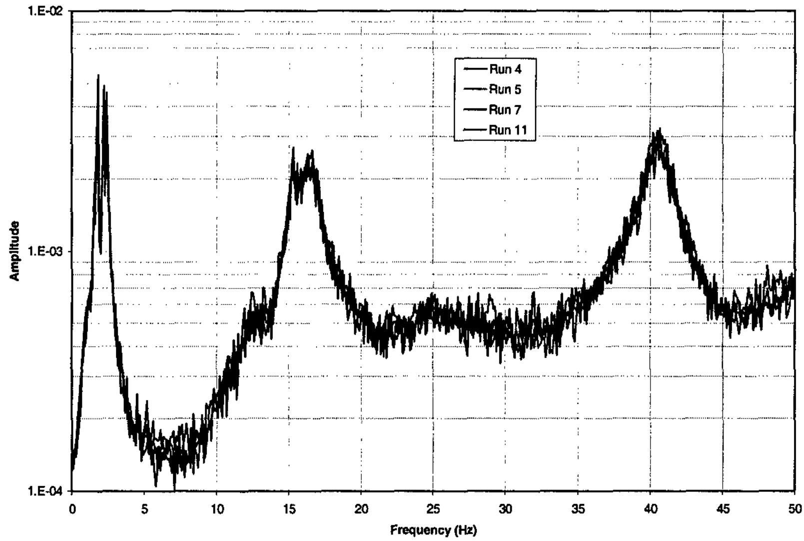

Figure 5: Torsional spectrum of hydro unit shaft motion

The frequencies below 5 Hz are somewhat enigmatic. Since the operating speed of the unit is 300 RPM, or 5 Hz, it was at first assumed that these frequencies correspond to fluid whirl, which generally occurs at speeds between 0.42 and 0.48 times operating speed [8]. However, the shaft lateral vibration data exhibited none of the signs of whirl. In addition, the three closely spaced subsynchronous peaks were stable and repeatable from run to run, as seen in Figure 6. Such stability and repeatability for three closely spaced frequencies does not correspond to the whirl phenomenon. In addition, similar spectral components have since been observed on hydro units at other sites. So, we hypothesize that these subsynchronous frequencies corresponds to the "rigid body" torsional mode on torsional springs corresponding to the bearing film stiffness in shear. Further investigation will be necessary to confirm this and to clarify the significance of these spectral components.

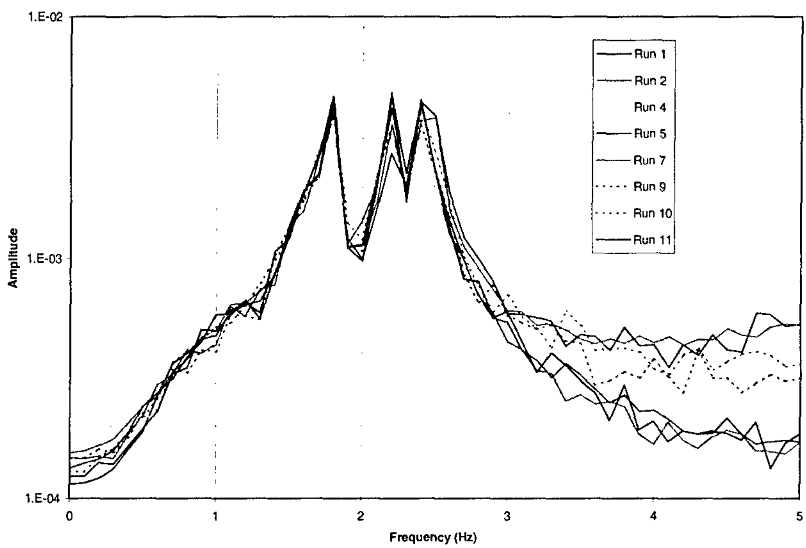

Figure 6: Subsynchronous torsional spectrum for hydro unit shaft

Several issues arose during the on-site data acquisition and analysis. Figure 7 shows some of the data of Figure 1 along with runs that had significant distortion due to tape errors. When the tape was changed, or even the axial location of the transducer was changed on the same tape, the spurious frequencies shifted. These spurious frequencies seem to be related to the encoded tape, and often interfered with the identification of shaft natural frequencies.

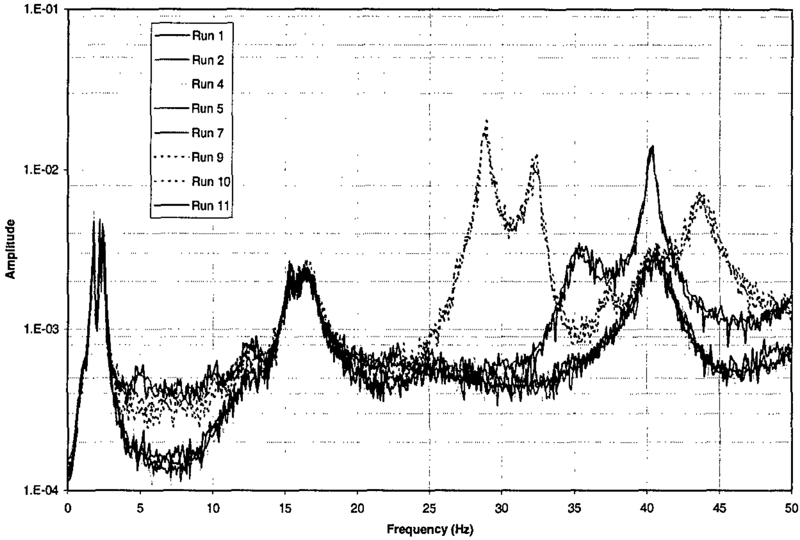

Figure 7: Torsional spectra showing encoded tape error spectral content

ID fan motors: The motors on the fossil-fired induced draft fan were constructed using rectangular cross section webs from the shaft to the rotor coil supports. The square end on the web was then welded to the circular shaft without machining to match the contours. The result has been a number of failures of the motors due to failure of the web welds. Two of these motors were instrumented to detect shaft natural frequencies and establish a baseline to track the changes that may be associated with web weld failure. Figure 8 shows the fan motor.

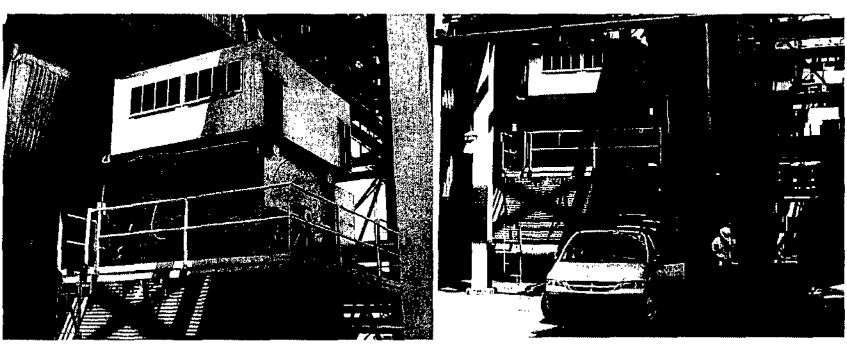

Figure 8: ID fan motor: (a) Motor housing; (b) scaled with minivan

Installation of the tape was more difficult on the ID fan than on the hydro unit due to the shaft size and the tight quarters. Figure 9 shows the installation of the transducer system.

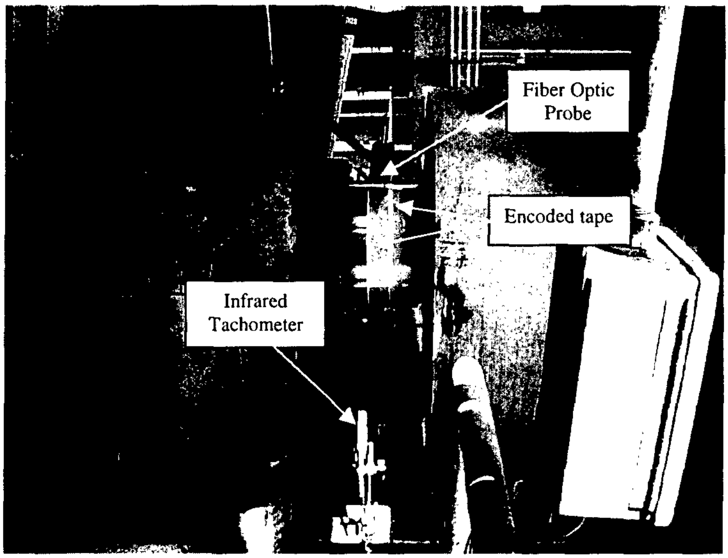

Figure 9: Tape, fiber optic probe, and tachometer installation on ID fan

In addition, the butt joint misalignment of the ends of the tape appeared to be exacerbated by thermal growth of the shaft. It was observed that a space between the ends appeared after heat up of the unit. This underlap, in some cases, caused saturation and malfunction of the analog demodulator. Figure 10 shows the results for one of the fans. The first mode appears to be about 10 Hz. Once again, it was observed that changing tapes or changing the shaft axial position of the optical probe on the encode tape changed some of the spectral content above 20 Hz. It is difficult to assess the remainder of the spectrum with high confidence due to the spectral content of the tape. However, most likely the second and third modes are at about 16 Hz and 19 Hz.

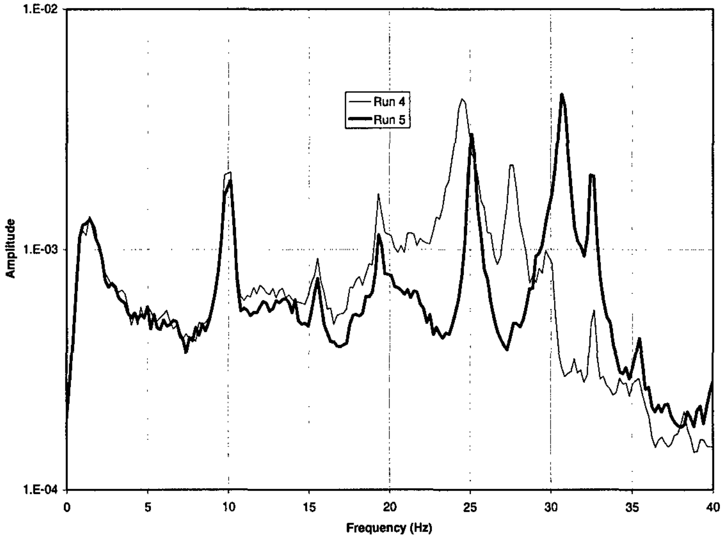

Figure 10: ID Fan motor torsional spectrum

Summary and conclusions: The techniques developed for detecting torsional natural frequencies in the laboratory were implemented on power plant machines that have experienced shaft cracking. The goals of the implementation project were to demonstrate the feasibility of field application, and to establish a baseline for each class of machine. The data acquired clearly demonstrated the feasibility of field implementation, and established baseline natural frequencies.

However, interference from tape related spectral content was experienced. This interference was not experienced in the laboratory due to shaft size, access, and environmental differences. It is believed that this spectral content is associated not with tape printing error or overlap, but was introduced by the installation.

Future work: Correction of the installation errors must be accomplished to remove ambiguity and make the technology widely accessible. This work is currently underway.

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